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SOME ASPECTS OF THE 200 GEV ACCELERATOR

Robert Rathbun Wilson

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Invited Paper Presented to

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Cambridge, Massachusetts

by

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On June 15th of this year a small band of determined physicists and engineers assembled at a curious place just outside of Chicago, Illinois, to design and build a 200 GeV proton synchrotron. The place, chosen because it is equally close to the Weston site, to Argonne National Laboratory, to the airport and to Chicago, is a lonely but large building at the Oak Brook Shopping Center. We have rented the whole tenth floor, a vast area that in the beginning had no partitions of any kind. Indeed communication was made by simply raising one's voice and will never again be so direct or so good. It has been a beehive of activity ever since, for technical people are attracted to where the "action is."

Our plan has been to pace ourselves so that we will have our designs, plans, costs and schedules all fixed by October 15th so that we can ask for the full authorization of funds for the 200 GeV facility for Federal Fiscal Year 1969, the one that starts July 1, 1968. W. A. Brobeck has brought his very considerable talents and resources to help us with engineering problems and with estimates of costs of accelerator components. The architect-engineering consortium, DUSAF*, managed by W. Alexander, is designing the construction of the conventional facilities and is determining their costs.

We decided to spend the first two weeks wildly, by considering all sorts of far-out schemes. However, on the last day of that period we buckled down and designed - in essentially one fell stroke - a separated-function machine which had a radius of one kilometer. That design has been refined throughout the summer and corresponds to the one I will discuss today. We are especially indebted to the physicists from Lawrence Radiation Laboratory, from Brookhaven National Laboratory, from the old MURA Laboratory and from the Argonne National Laboratory for giving us the benefit of their indispensable experience and help, without which I would have little to speak about here today. Physicists from the universities and from abroad have also "rallied round." We solved the perennial visitor problem; we simply put them to work. The number of people has been so large that I cannot even try to give proper credit - but I hope that will be done in future publications by the contributors themselves.

The master plan for the site is shown in Figure 1. The ring has been located in the southwest corner. We have tried to gather in one place as many functions of the synchrotron as possible and at that place we plan

*Daniel, Urbahn, Seelye & Fuller, a joint venture of Daniel, Mann, Johnson, & Mendenhall; The Office of Max O. Urbahn; Seelye Stevenson Value & Knecht, Inc.; and George A. Fuller Company.

to erect a high-rise building in which nearly all of our eventual population of roughly 2,000 people will find themselves. The particular location of the building has largely been determined by a lovely forest on the western side of the site. It is here, too, that we have discovered the high ground of our otherwise very level site: we call it the Presidential Range, the highest peak of which has been named Mount Ramsey. I might add that this peak is notable because its height is variable, 20% higher during the corn season! A detail of the master plan is shown in Figure 2 where it can be seen how the linear accelerator, the booster, the injection point, as well as the point of extraction of our main external beam, all are located around the position of the main building which is roughly indicated in Figure 3. We will, of course, have to make detailed calculations to insure that the building is really in a radiation-free area.

We wanted from the outset to have the option of going from 200 GeV as the immediate goal to higher energy at a later stage. We considered the ingenious "expanditron" idea generated at Berkeley, and then we considered another scheme in which a superconducting storage ring would be built nearby. In this scheme, the storage ring is first filled from the synchrotron, then the field of the storage ring is very slowly raised until the energy reaches, say, 500 GeV.

Because the expanditron implied a lengthy shutdown for the expansion, we decided to try to build a magnet which would have a large enough radius to reach eventually a substantially higher energy, but for which we would initially install a power supply capable of reaching only 200 GeV.

One of the first things we learned about proton synchrotrons is that nearly all of the radiation is deposited in a region extending downstream from the target a few hundred feet, i.e., in the first half or so of a betatron wavelength. This consideration, together with a desire for simplicity of control, has led us to focus our attention on one single extraction point from which the external proton beam would be led into a three-mile-long distribution system which will feed a variety of experimental areas as shown in Figure 1. We will build special magnets, beam deposition devices, handling devices, and shielding in the area of high radiation - and we will insist that the beam in fact be deposited in this region. Then an inadvertently large deposition of the beam anywhere in the remaining 98% of the magnet would constitute a reason to shut it off and make an appropriate repair. This point of view gives nearly two orders of magnitude advantage in radiation problems for the "cool" part of the synchrotron.

This consideration gave us the courage to design the bending magnets shown in Figure 4a and 4b in which a modified "window-frame" coil construction is used. In fact, as shown in Figure 5, the small effect of the edge of the gap fortuitously turned out to be beneficial for it tends to compensate for the effect of saturation of the magnet at high fields, which produces a decrease of the field toward the center of the aperture.

Because we have placed magnets on as much of the circumference as we dared, the magnetic field for an energy of 200 GeV is 9 kG, i.e., a bending radius of 743 meters. At 18 kG, the field, according to calculations made for us at Berkeley, still shows little or no effects of saturation.

At 21 kG, because of the compensating effects, the field is better than at small fields, but at 22.5 kG it is no good at all. Perhaps by using such techniques as crenellating the magnet it can be made to reach 22.5 kG. The saturation of the yoke of the magnet would be about 75% at this field.

A two-foot-long model of the magnet that is full scale in cross section has been constructed for us at the University of Wisconsin. It will be tested for its magnetic properties at Argonne National Laboratory. Another model has been made that is 20 feet in length in order to test structural effects of the high currents in the coil. This is just the beginning of a series of models that should eventually end with an actual prototype.

Each of the 744 bending magnets will be 6.27 m (20 feet) long. They will be placed in the separated function lattice, prepared by L. C. Teng and A. A. Garren from their calculations using the computer at the Argonne National Laboratory. There are six long straights each of which is 54 m (178 feet), six medium straights of 29 m (95 feet) length, and 192 mini-straights each 2.5 m (8 feet) long. The long straights are modified Collins straight sections and the medium straights are made simply by leaving out the four bending magnets that are located between the quadrupole focusing magnets. If the mini-straights turn out not to be full of correction coils, it might be possible eventually to add short bending magnets in order to attain an additional 5% increase of the energy. One of the six superperiods of the lattice is illustrated in Figure 6. Each unit cell contains two quadrupoles, one focusing, the other defocusing, that are separated by a distance of 30.5 m (100 feet). The four bending magnets of each half-cell are separated from each other and one of the quadrupoles by 0.3 m (1 foot) except for the mini-straight that is next to the other quadrupole. Table I summarizes the parameters of the main accelerator.

The current cycle of the magnet is shown in Figure 7a and consists of an 0.8 sec filling time followed by a rise to full current in 1.6 sec. A flat-top can last for a duration of between 0 and 1.0 sec, and then the descent time is 0.6 sec to give a complete cycle time of from 3 to 4 sec, depending on the length of the flat-top. An intensity of 5×10^{13} protons per pulse is the design goal corresponding to this cycle.

The curvature of the beginning of the rise of the current is to allow the rf power to be efficiently used, and the particular shape corresponds to the characteristics of the ferrite used in the rf tuners. The curved form indicated at the bottom of the descent is to allow the magnet to recover from its excitation to high field.

The average power dissipated in the magnet for the cycle of Figure 7a will be roughly 12 MW and the peak power will be about 65 MVA. These are both small enough so that it may be possible to connect the magnet directly to the line without using motor generators.

The option for increasing the energy might be done by using the cycles shown in Figure 7b in which the rate of rise is kept constant so that the rf capability need not be increased. Higher energy would then imply a longer cycling time and hence a correspondingly lower average intensity.

Two kinds of bending magnets are to be built, the aperture of one being 5.0 cm (2 inches) in height and 10 cm (4 inches) in width, while the aperture of the other is to be 3.8 cm (1.5 inches) high and 12.5 cm (5 inches) wide. The different magnets allow the aperture to adapt roughly to the undulating shape of the beam that is characteristic of strong focusing. This is equivalent to using an aperture that is 2 inches x 5 inches everywhere and it gives a substantial reduction of the stored energy. The number of turns in the coils have been made proportional to the gap heights so that the coils can be placed in series. In order to keep the voltage on the magnets low, i.e., several hundred volts, some 24 power supplies will be located in utility buildings that are to be uniformly distributed around the ring.

The magnets are to be made of punched laminations that are a few mm in thickness and, as indicated in Figure 4a, will be fabricated in two halves. Several methods of fabricating the magnets are being considered. The laminations might be welded together; they might be dry-stacked and then clamped together; or they might be potted within an I-beam as is indicated in Figure 4b. The coil will be fabricated of copper bars which might be covered by a thin layer of alumina and then potted in place with a radiation-resistant epoxy in a prestressed manner. The two halves could then be keyed and welded together as shown - a thin stainless-steel donut having been inserted and compressed between the halves before the welding. The I-beams would make the magnets rigid enough so that a base is unnecessary. It is also clear that the magnets can only be used as integral units; if something goes wrong, the whole unit would have to be replaced. Handling devices will be designed to do just this, eventually by remote control.

A possible design of a quadrupole lens that keeps the same external size of the magnet is shown in Figure 8. The turns of the coil are adjusted so that the value of the gradient will be correct if the magnet and quadrupole coils are connected in series. The gradient in the quadrupoles should be about 150 kG/m at 200 GeV excitation. The gradient in the quadrupole magnet shown in Figure 8 should reach a few times this figure without saturation. It should also be pointed out that it would be possible to operate with a lower ν value at higher energy, which would require less excitation of the quadrupoles - a feature possible only in a separated-function lattice.

Support Mechanism

The bending magnets will weigh about ten tons each and are rigid enough to be supported at their ends by three adjustable jacks as shown in Figure 4b. The radial and vertical position of an end of the magnet as well as the tilt can be adjusted by relative motions of the jacks. The azimuthal position is not critical but it will also be adjustable by a set-screw. Small electrical transducers can be placed in the jacks to indicate relative positions.

The alignment of the magnets, however, is to be done by means of wires stretched from one unit cell to the next, i.e., 200 feet from one quadrupole to the next similar quadrupole, see Figure 9. The off-set in passing the opposite kind of quadrupole is about 50 cm (20 inches) and the position of the wire here can be sensed by passing a small current through it and using a ferrite core device in the manner of a familiar beam-position detector, i.e., by bucking two oppositely placed coils on the ferrite core through which the wire passes. The intervening bending magnets can also be lined up on the same wires, although the orbit is relatively independent of the positions of the bending magnets. The tilt of these magnets is critical, however, and this will be adjusted either by a spirit level or perhaps by a mercury leveling device. An accuracy of a few thousandths of an inch seems possible - and necessary - to attain in the placement of the quadrupole magnets.

A monument-caisson will be set several feet into the ground at the ends of each of the long straights to which the reference wires can terminate, but otherwise no particular foundations will be used for the magnets except the tunnel floor which will probably be a thick slab of concrete. The tunnel is to be about ten feet wide and eight feet high and will be set deep enough in the ground so as to be in relatively stable earth. The stretched wires should provide a method of continuously monitoring and adjusting the radial and vertical positions of the magnets even if the ground should move.

Thankfully, we are being given assistance in the design of many of the components by physicists and engineers at the Lawrence Radiation Laboratory in Berkeley. Typical of this collaboration is the rf system. Q. A. Kerns will continue his design work at Berkeley for about another year: he has joined the National Accelerator Laboratory and will eventually bring his work to Illinois. Because we have slowed down the average rate of rise of the field by about a factor of two and because of the curved toe of the rate of rise, Kerns has found it possible to reduce the number of cavities to 14 that are operating plus two spares - all of which can be placed in one of the medium straights. The injection energy will be 10 GeV, corresponding to an injection field of about 500 gauss, hence only 0.4% change in the frequency of 53.5 MHz need be made. The peak voltage per cavity, 265 kV, will give the necessary energy gain per turn, 2.75 MeV, at a phase angle of 50°. Nearly as much power will go into the beam as into copper and ferrite losses - the total of which comes to about 2 MW.

We are planning to build a 200 MeV linac very similar to the one being built at the Brookhaven National Laboratory for their improvement program. In fact, D. E. Young, who is in charge of our Linac Section, is presently collaborating with the Brookhaven people in their linac work. We plan to have a temporary laboratory built on the Weston site by next spring in which he and his collaborators can begin to install parts of our linac.

The design work on the booster synchrotron has largely been going on at Berkeley under the direction of J. M. Peterson. S. C. Snowdon, A. van Steenbergen, R. Billinge, R. Yamada and L. C. Teng have been hard at work at the National Accelerator Laboratory and now it appears that we are developing the capability of making our own final booster design. We have chosen the radius to be 75 m on rather an arbitrary basis - 50 m seemed too small, and 100 m seemed a bit large. We have also chosen to make it a fast-cycling booster at a frequency of 15 Hz which corresponds to the 0.8 sec filling time of the main ring. We expect that eventually the magnets will not be too dissimilar from the magnets of the main ring both in respect to size and to the support mechanism. We hope to be able to build the booster in such a manner that it could also be used as a slow booster if we so choose at a later time. Jack Peterson will elaborate on the booster design in his talk.

E. L. Goldwasser, the Deputy Director of the Laboratory, has been in charge of the design of the experimental areas and has had great cooperation this summer from the physicists of this country, as well as those from abroad who have come to help us. He will describe our plans in detail elsewhere so I will give only the roughest outline here.

As I have said earlier, we plan to emphasize the use of a single external proton beam that can be led down a straight tunnel along the three-mile line that is available on the site for an experimental area, see Figure 1. The beam will be switched or split from this tunnel onto target stations that are to be located off to the side as shown in Figure 10.

We currently plan to provide for possible internal targeting at one of the long straights either immediately following or preceding the main beam extraction point. Two independently controllable secondary beams have been designed for this internal target; one at an energy of 150 GeV and coming off the target at an angle of 1 mrad, and the other one at an energy of 50 GeV and at a larger production angle. An internal target intensity limit will be set at 5×10^{12} protons per pulse which will generate about the same activity in the main ring as the extraction of 5×10^{13} protons per pulse in the external beam. The size of the tunnel near the internal beam area will be much larger than the tunnel in a cool section of the ring. It will have cranes, etc., and will be arranged to accommodate future conversion to a second external proton beam. We expect it to be used immediately after a beam is obtained in the machine and until the external beam has been tuned up.

Initially we adopted as a minimal experimental program one which would include two external target stations and one internal target, all to feed nine experimental beams of which six might be in operation at any one time. Our Advisory Committee suggests that this so-called reduced scope is inadequate and has recommended that the initial plan should be scaled to handle about 25% of the national program in high energy physics. This would mean about seven counter beams and whatever bubble chamber beams may be required.

Accordingly we have designed the array shown in Figure 9 which shows nine real beams issuing from two external targets, the beams for the most part being independently controllable. We have also added the concept of a thin target station around which proton bombardment experiments can be arranged with only minimal shielding requirements. A model design provides three beams from this target.

A. W. Maschke has been responsible for the designs for extracting the beam, placing it on target, and then dumping it. He, too, will give a more detailed account of his work elsewhere.

In addition to the plans I have described, we also have considered a number of options for the construction of which we would hope that funds might eventually be provided. Among these are the option to expand our experimental area, the options of increasing the energy and the intensity, and the option of building a bypass on which might be located a small storage ring. The storage ring would also provide for the possibility of accelerating anti-protons. Other external beams might also be developed and, using them, a large storage ring might eventually be built and filled. We are presently trying to assess the feasibility and costs of all of these schemes.

The work I have described here has been due to the strong group of fellow-physicists who have joined the Laboratory. It has been a privilege for me to report their activities and that of our visitors and helpers, and I regret not to have given proper credit to each for his Herculean efforts of this summer. With such a group I am confident that a beam can be obtained by the summer of 1972 if funds are authorized on schedule.

This work was done under auspices of the U. S. Atomic Energy Commission.

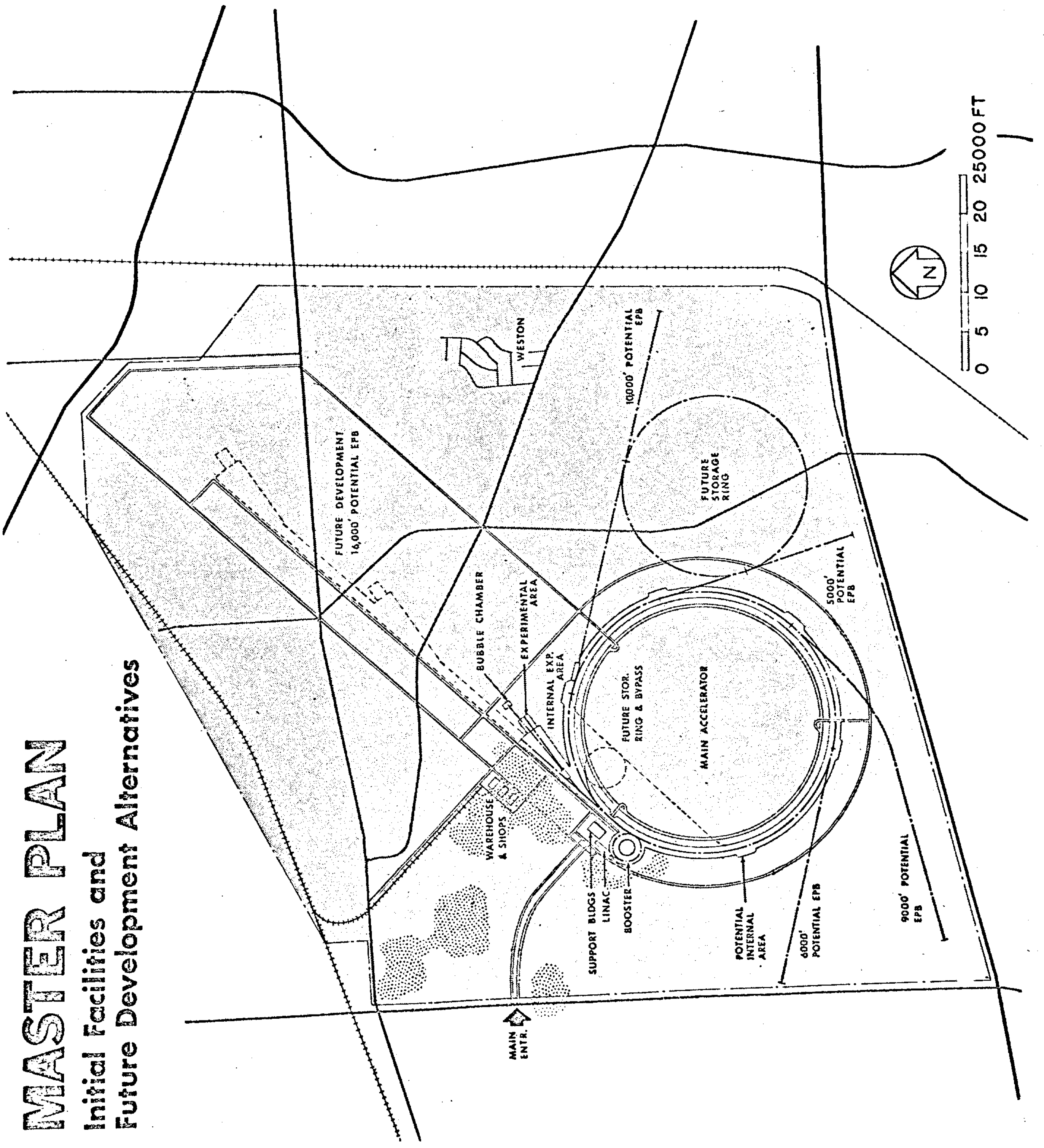
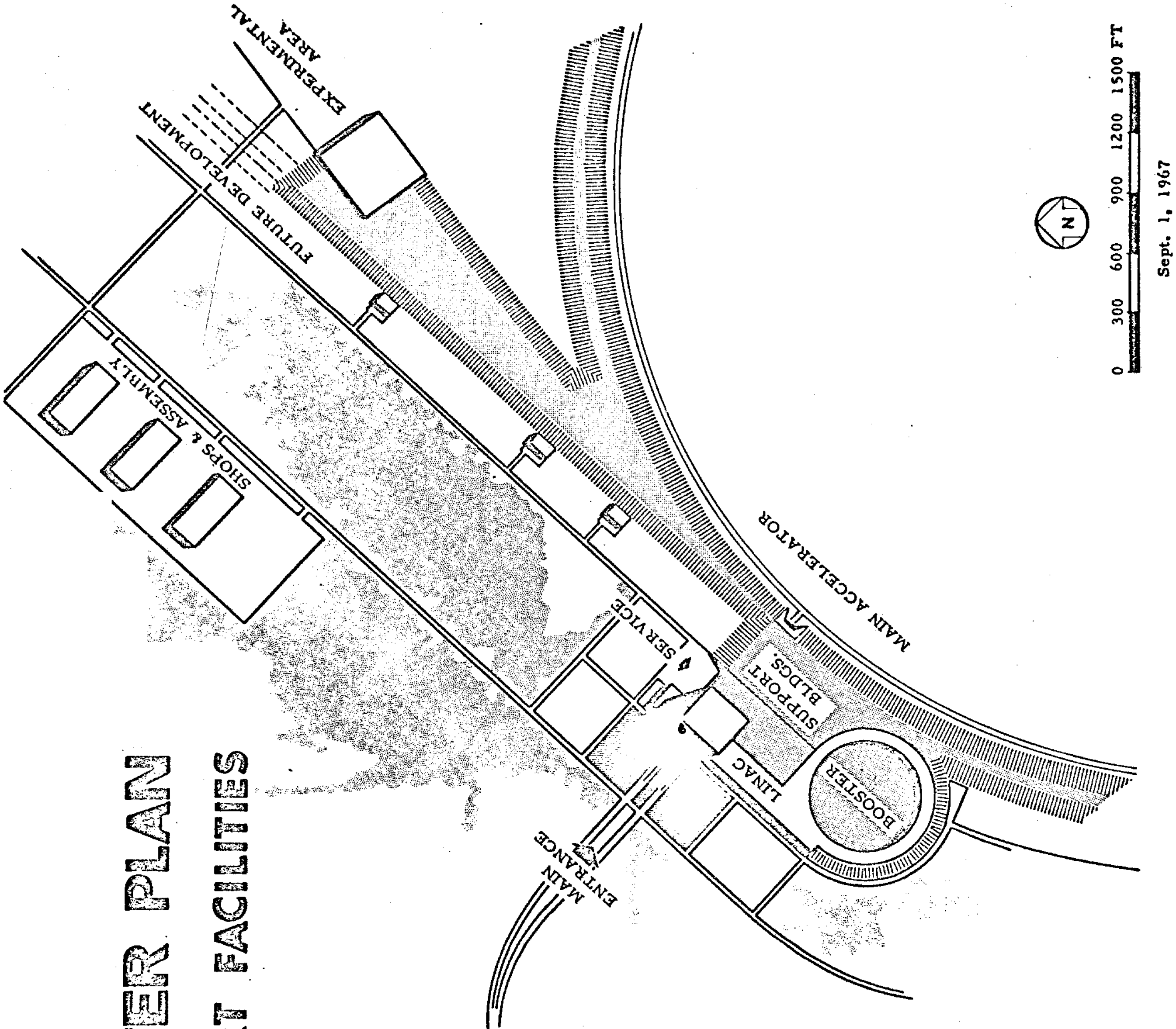
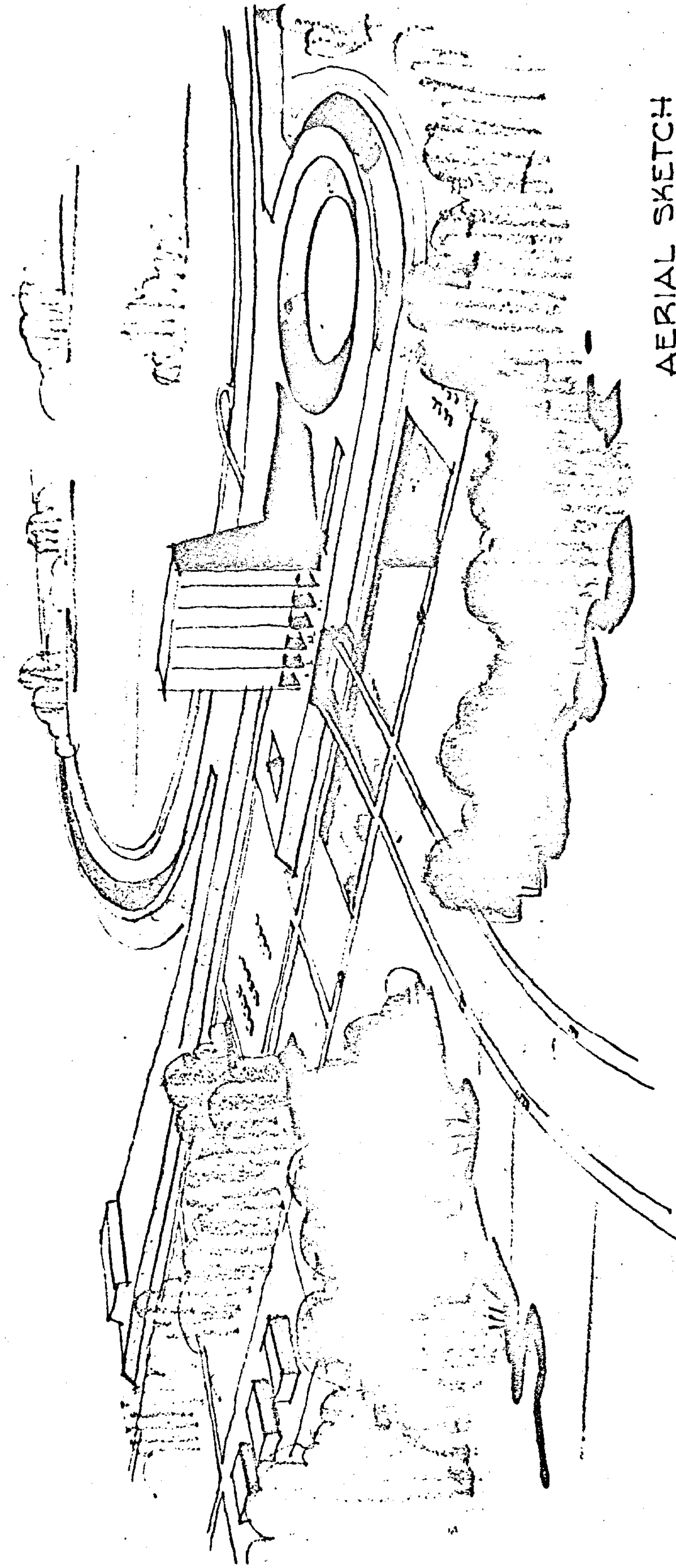

MASTER PLAN
Initial Facilities and
Future Development Alternatives
MAIN ENTR.
WAREHOUSE & SHOPS
SUPPORT BLDGS
LINAC
BOOSTER
POTENTIAL INTERNAL AREA
6000' POTENTIAL EPB
9000' POTENTIAL EPB
MAIN ACCELERATOR
FUTURE STOR. RING & BYPASS
INTERNAL EXP. AREA
BUBBLE CHAMBER
EXPERIMENTAL AREA
FUTURE DEVELOPMENT 16,000' POTENTIAL EPB
5000' POTENTIAL EPB
FUTURE STORAGE RING
10,000' POTENTIAL EPB
WESTON
N
0 5 10 15 20 25000 FT

Fig.1



MASTER PLAN
SUPPORT FACILITIES

Fig. 2



AERIAL SKETCH
SUPPORT FACILITIES

DUSAF
SEPT. 1, 1967

Fig.3

Fig. 4a

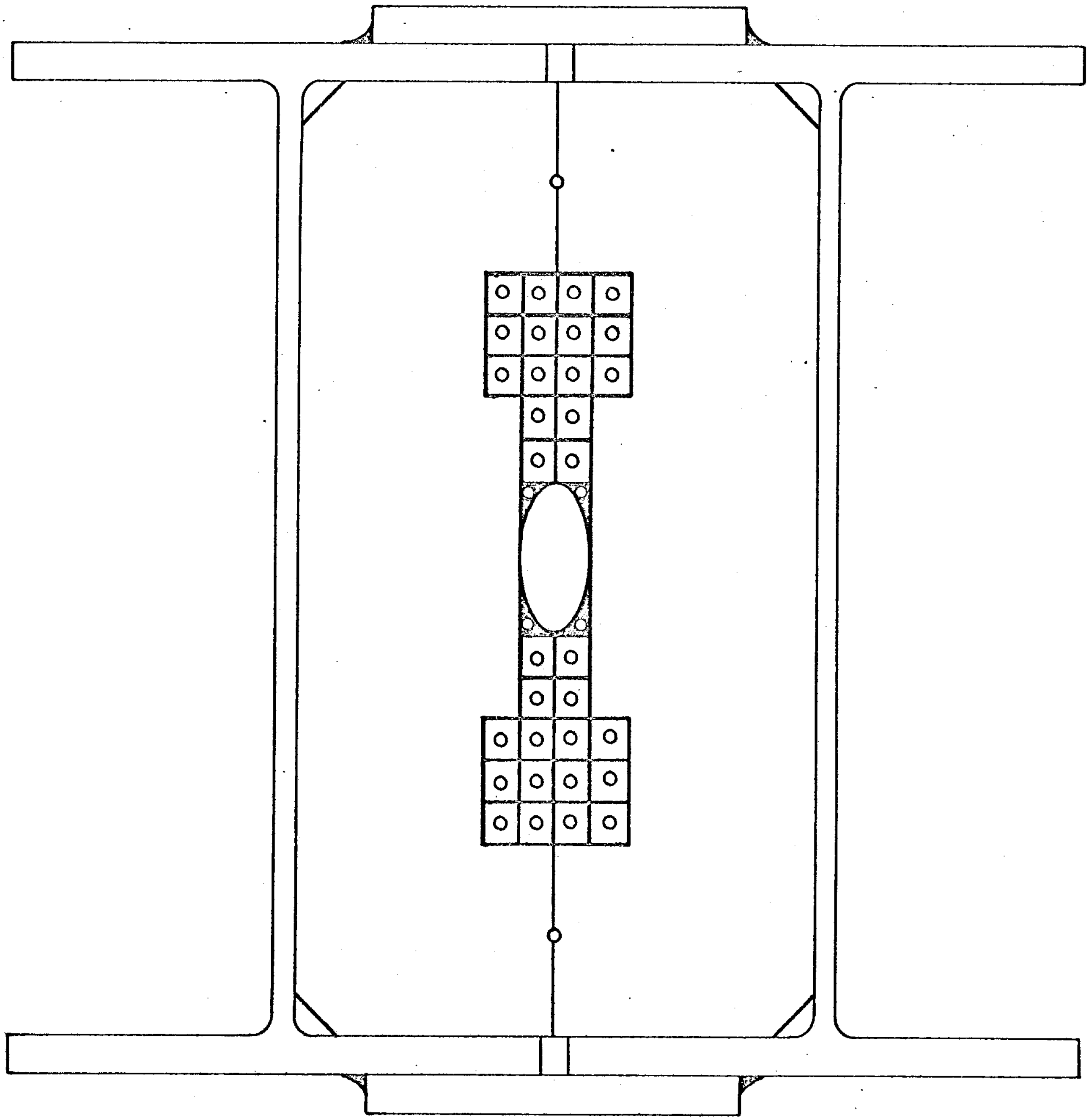
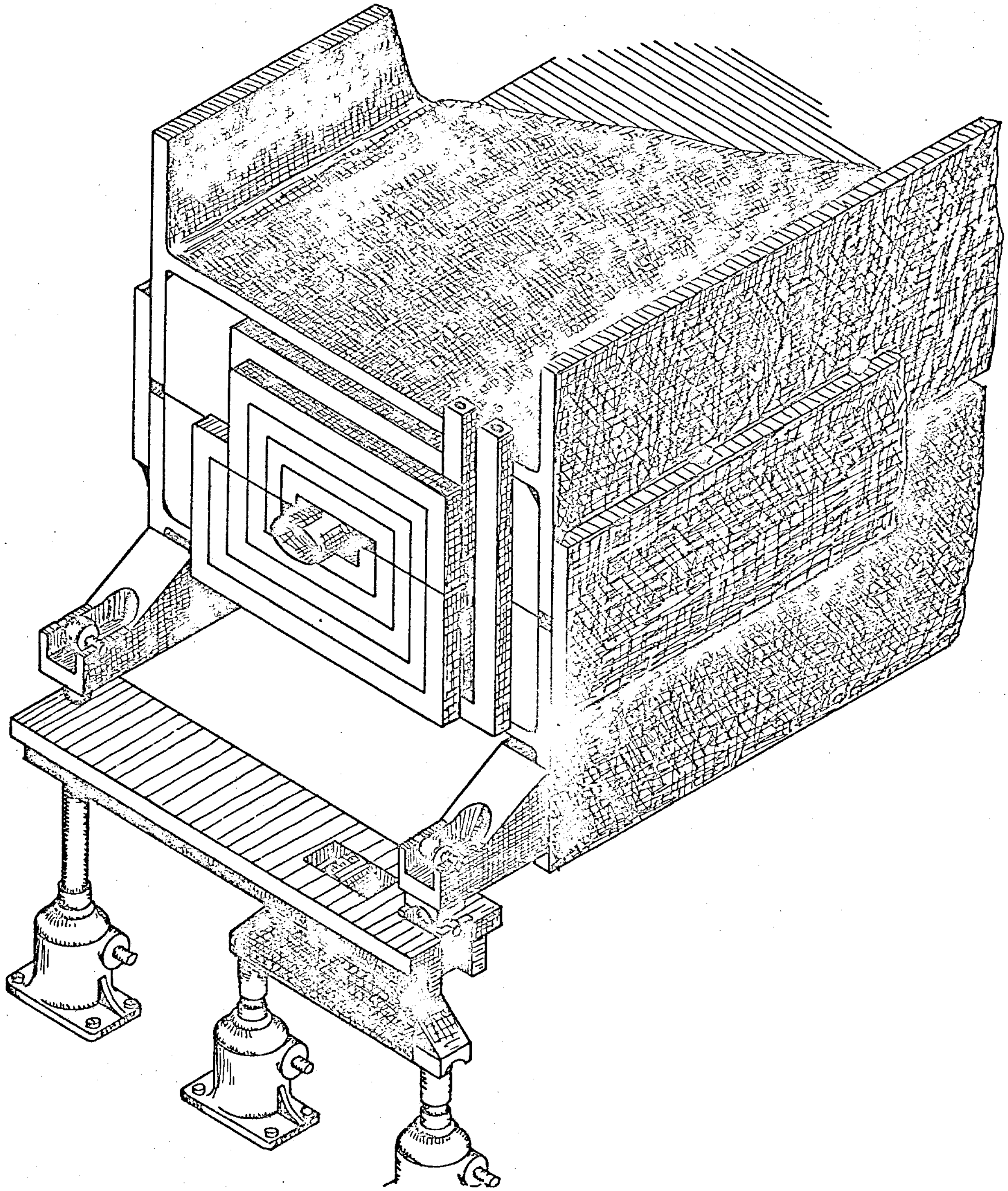


Fig.4b



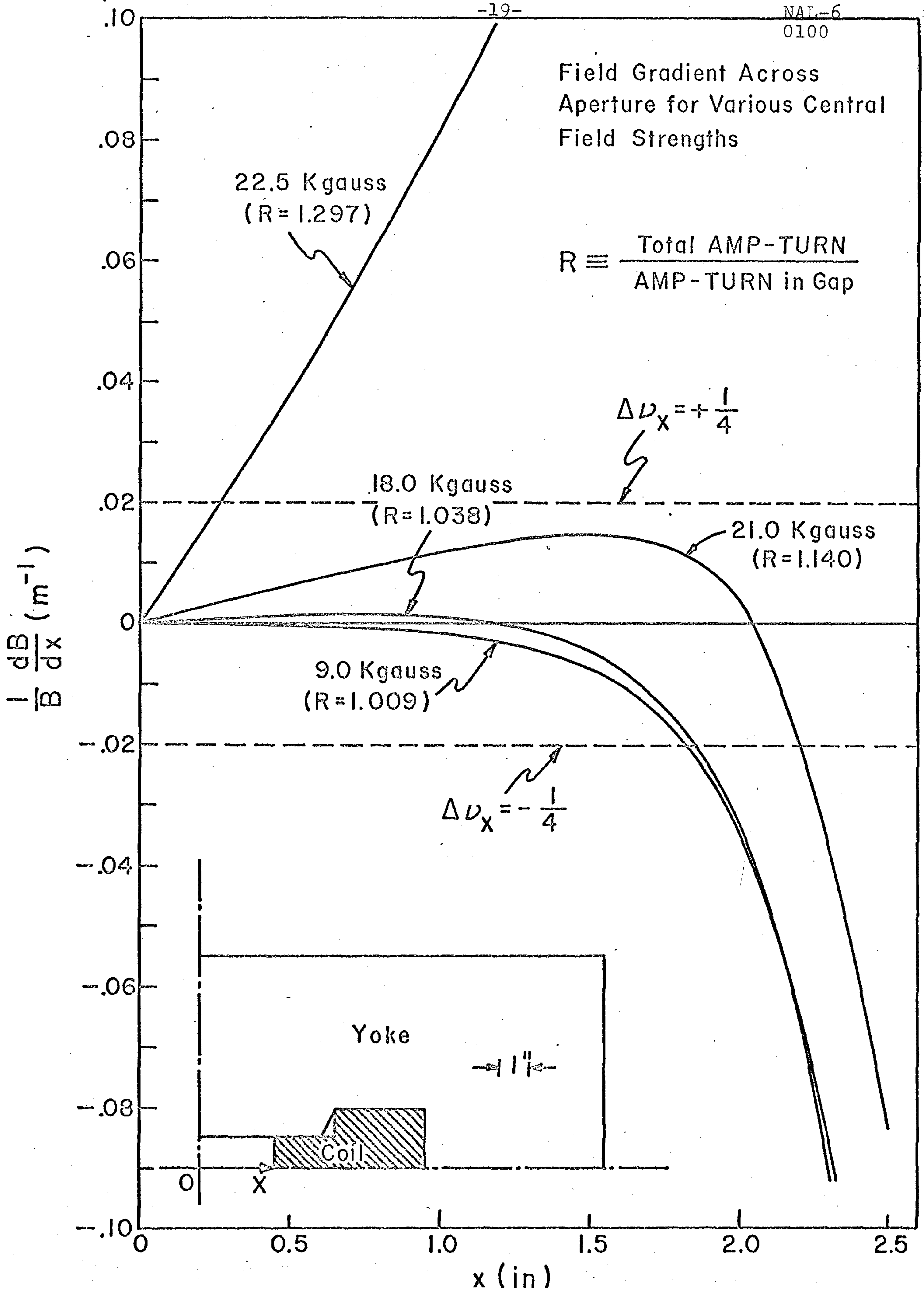
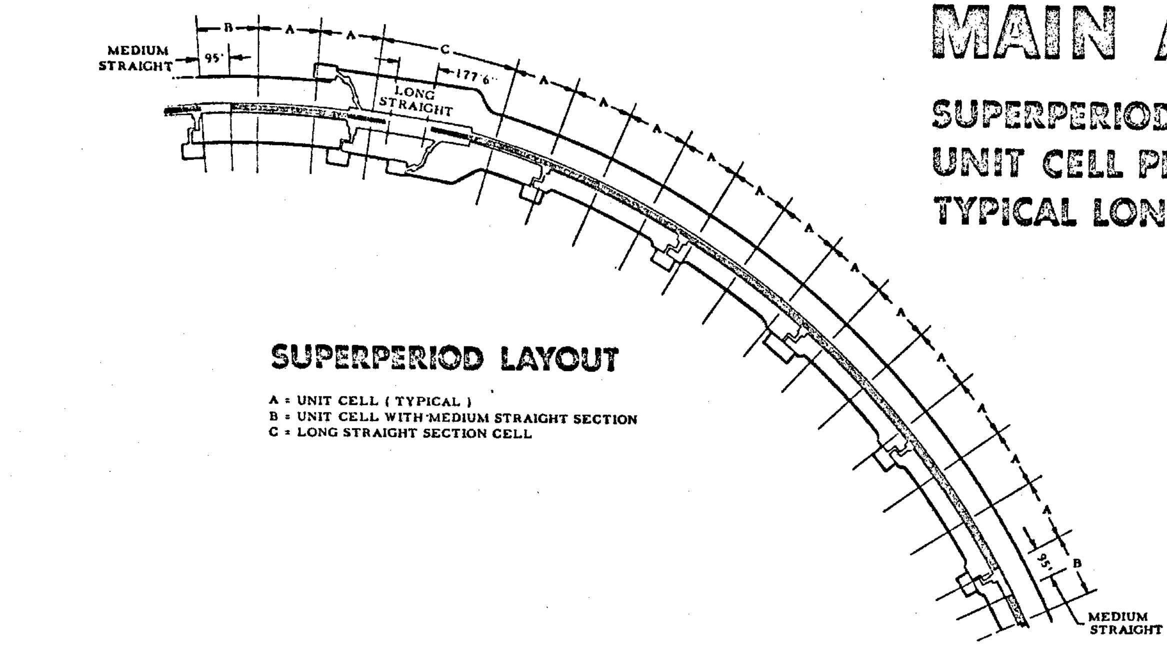

Field Gradient Across Aperture for Various Central Field Strengths
$R \equiv \frac{\text{Total AMP-TURN}}{\text{AMP-TURN in Gap}}$
22.5 Kgauss (R = 1.297)
18.0 Kgauss (R = 1.038)
21.0 Kgauss (R = 1.140)
9.0 Kgauss (R = 1.009)
$\Delta\nu_x = +\frac{1}{4}$
$\Delta\nu_x = -\frac{1}{4}$
Yoke
1"
Coil
O
X
$\frac{1}{B}\frac{dB}{dx}\ (m^{-1})$
x (in)
.10
.08
.06
.04
.02
0
−.02
−.04
−.06
−.08
−.10
0.5
1.0
1.5
2.0
2.5

Fig. 5

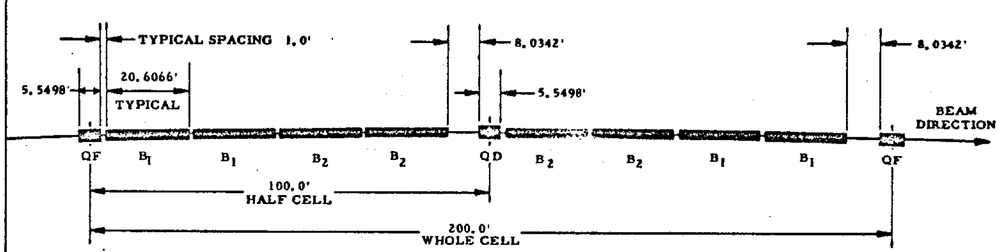
MAIN ACCELERATOR

SUPERPERIOD LAYOUT, UNIT CELL PLAN & TYPICAL LONG STRAIGHT SECTION PLAN

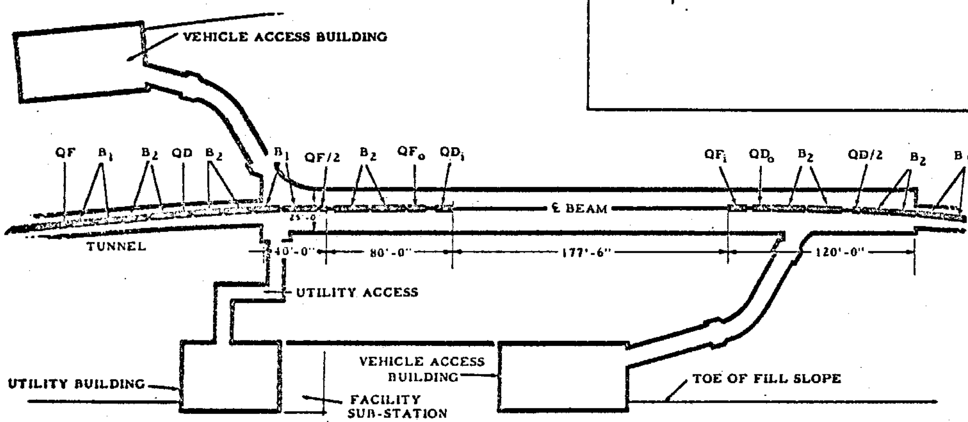


SUPERPERIOD LAYOUT

A = UNIT CELL (TYPICAL)
B = UNIT CELL WITH MEDIUM STRAIGHT SECTION
C = LONG STRAIGHT SECTION CELL



UNIT CELL PLAN



LONG STRAIGHT SECTION

LEGEND

QF = QUADRUPOLE MAGNET FOCUSING
QD = QUADRUPOLE MAGNET DEFOCUSING
B_2 = BENDING MAGNET 2" x 4" APERTURE
B_1 = BENDING MAGNET 1.5" x 5" APERTURE
QF_o = OUTER COLLINS QUADRUPOLE, FOCUSING
QF_i = INNER COLLINS QUADRUPOLE, FOCUSING
QD_o = OUTER COLLINS QUADRUPOLE, DEFOCUSING
QD_i = INNER COLLINS QUADRUPOLE, DEFOCUSING
QF/2 = HALF COLLINS QUADRUPOLE, FOCUSING
QD/2 = HALF COLLINS QUADRUPOLE, DEFOCUSING

Fig. 6

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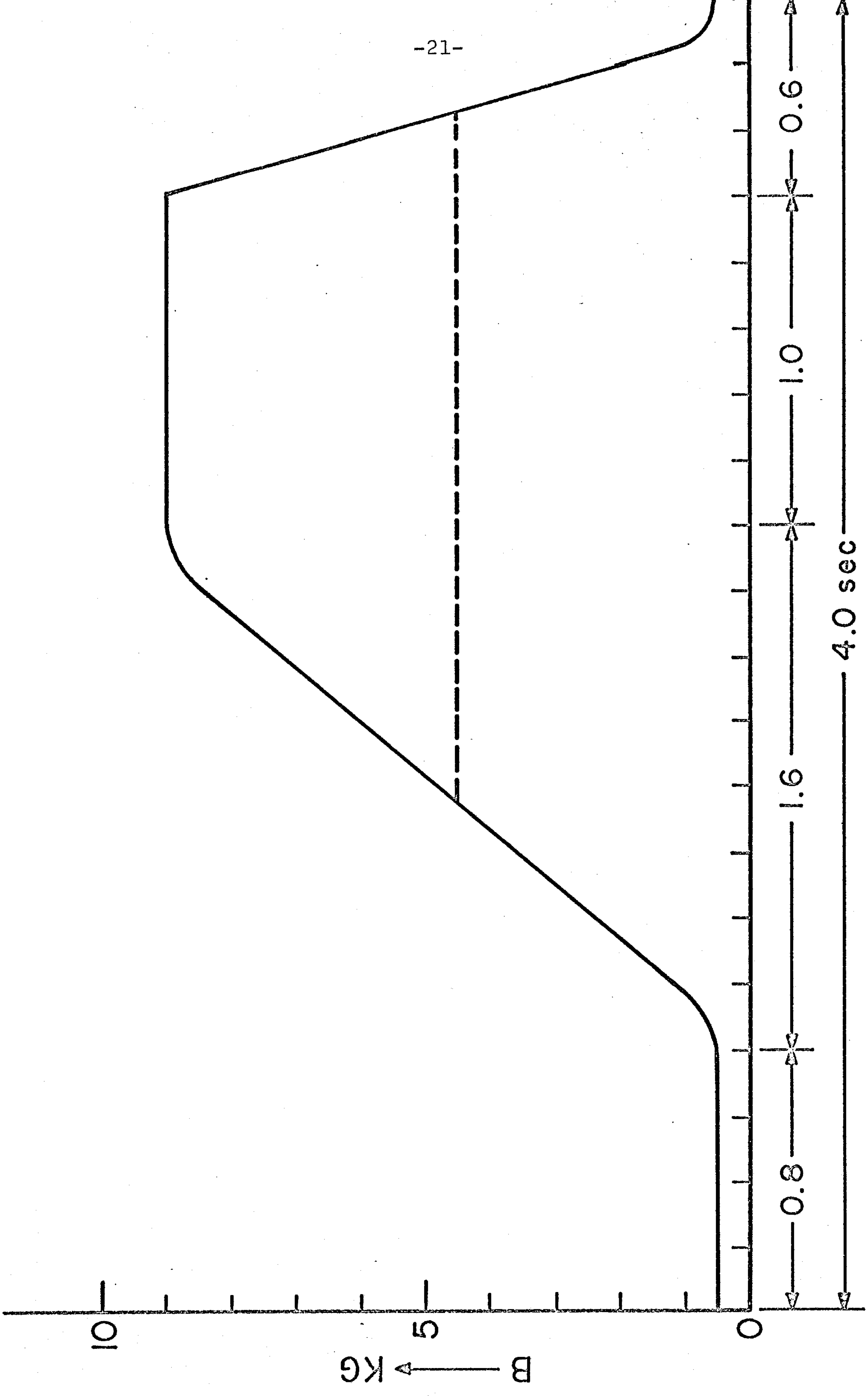


Fig. 7a

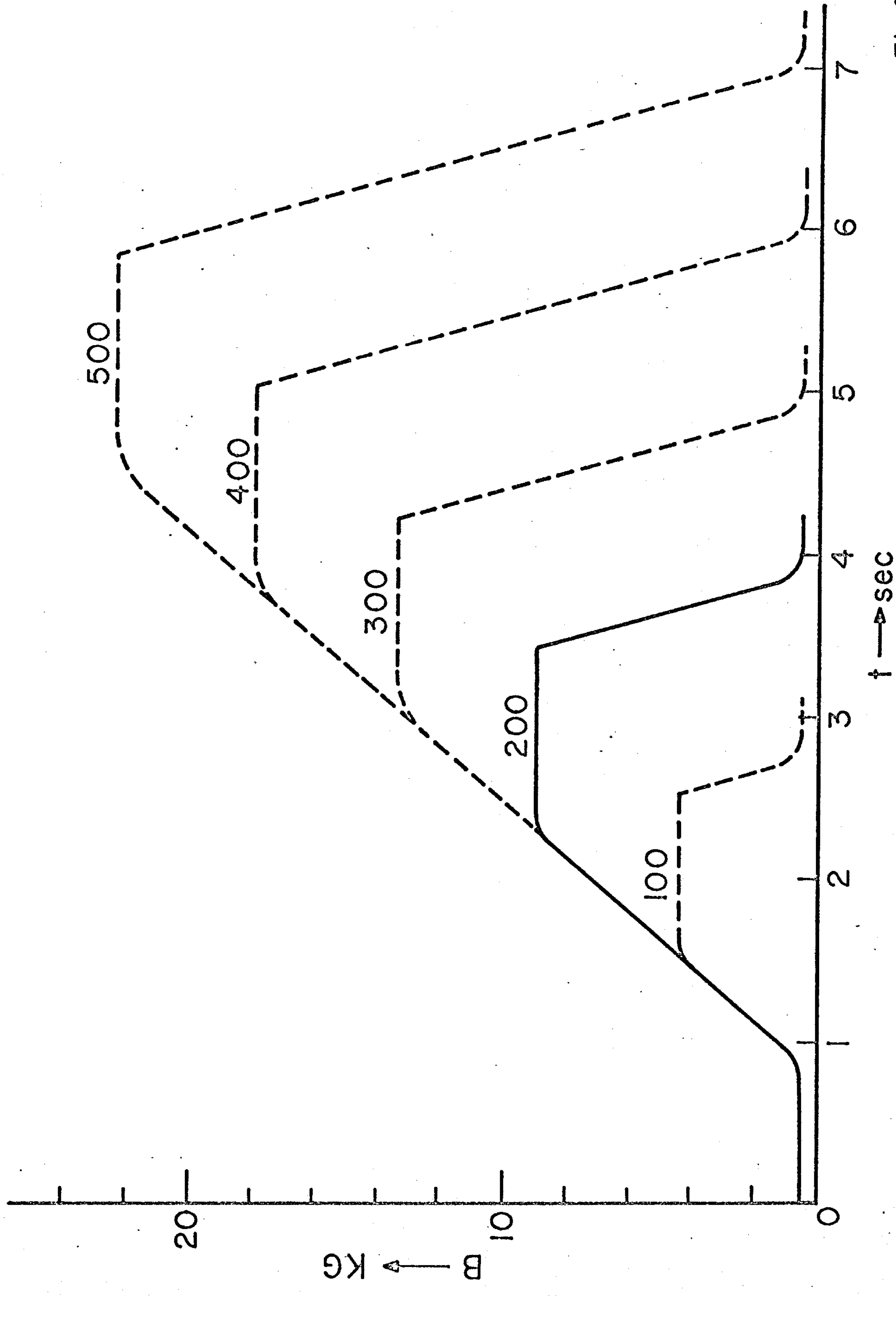
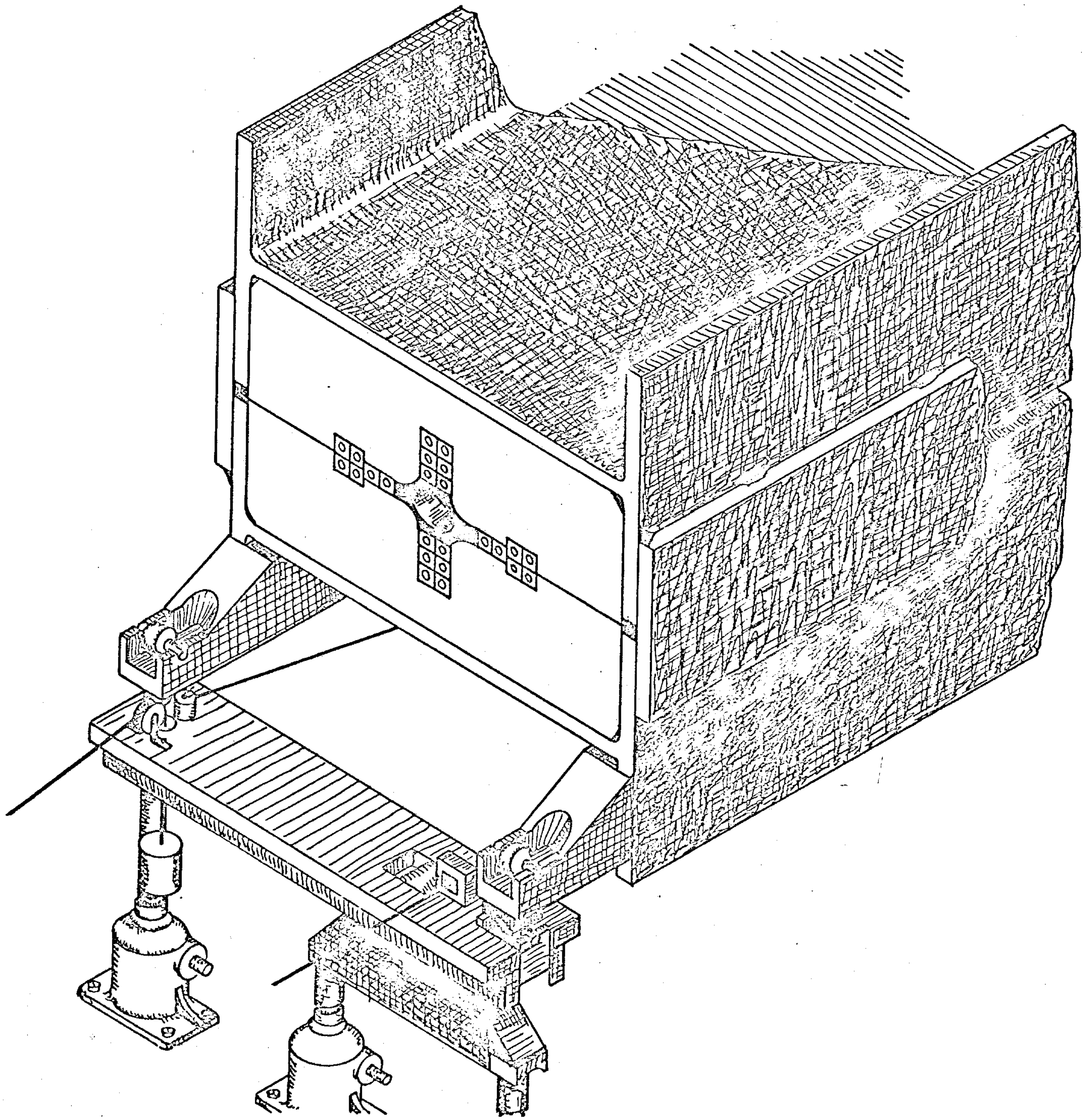
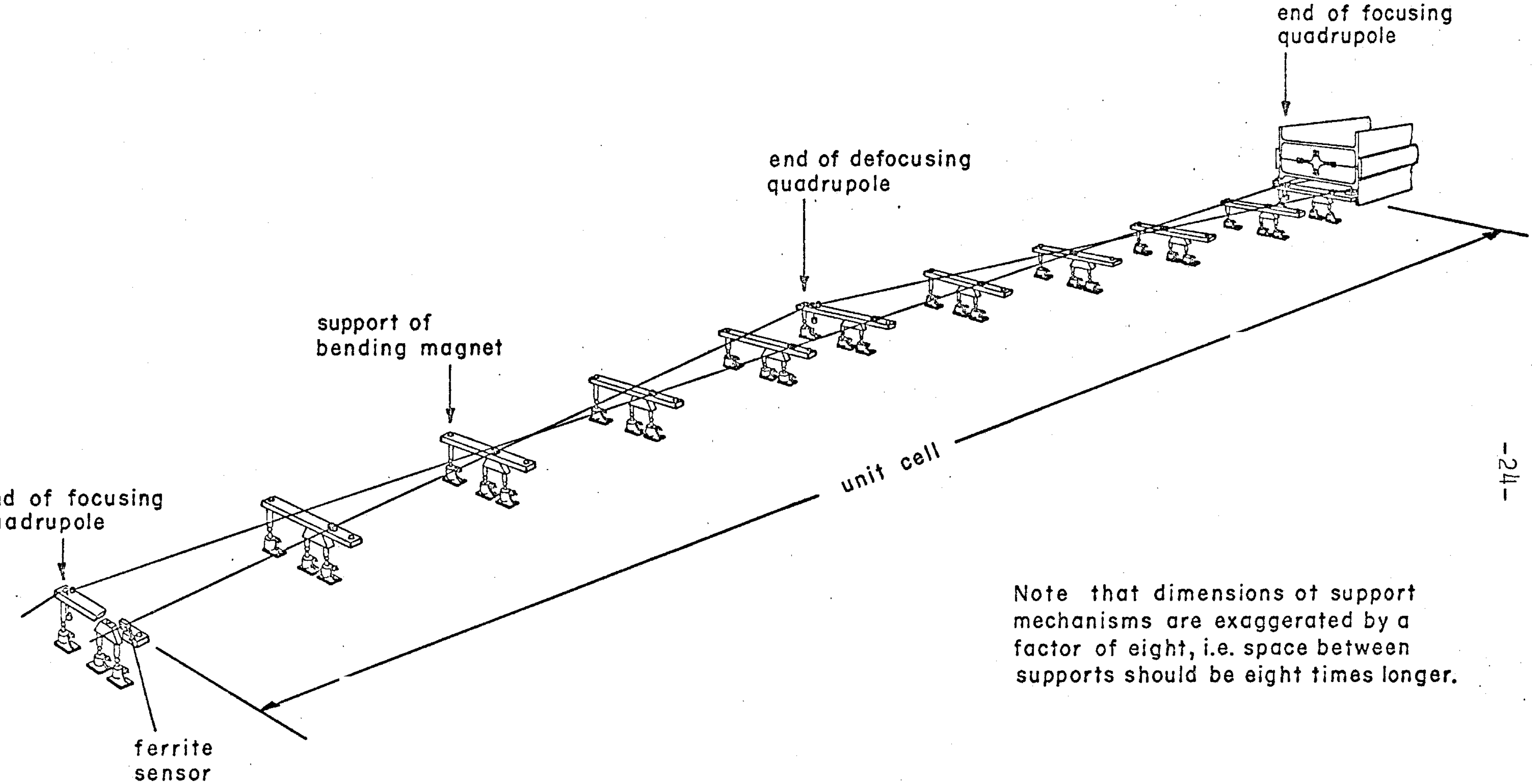


Fig.7b

Fig.8





Note that dimensions of support mechanisms are exaggerated by a factor of eight, i.e. space between supports should be eight times longer.

Fig. 9

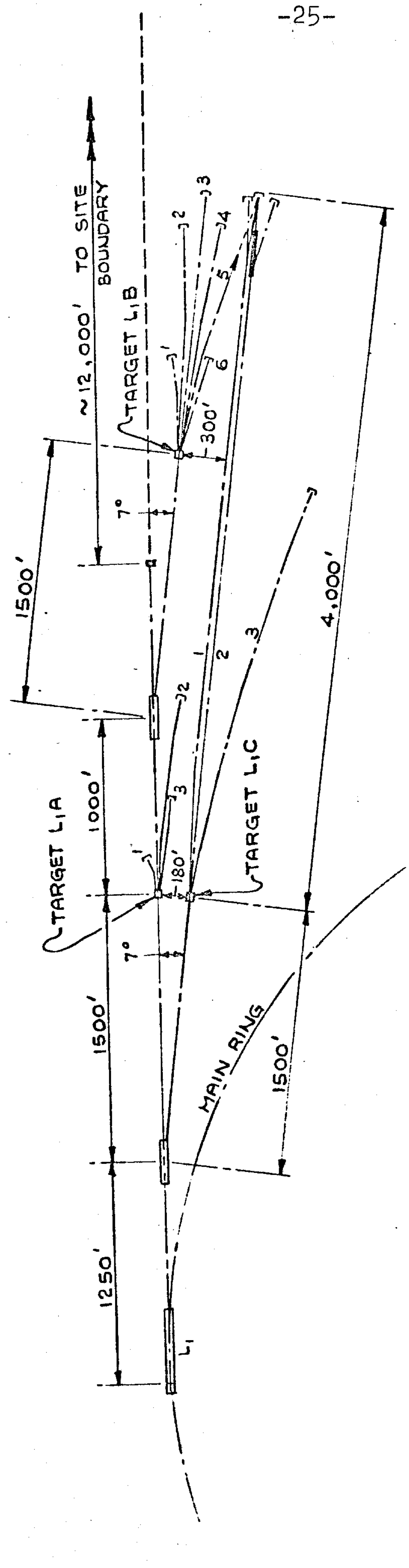


Fig. 10

EXTERNAL EXPERIMENTAL AREAS

SCALE: 1" = 800'

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TABLE I

Kinetic Energy	400	Gev
Radius (circumference/2π)	1000	Meters
Magnetic Radius	742.99	Meters
Magnetic Field	18	Kg.
Betatron Oscillation Frequency	20 1/4	
Transition Kinetic Energy	17.2	Gev
Number of Super-Periods	6	
Number Long Straights	6	
Number Medium Straights	6	
Number Short Straights (including 2 per long straight)	192	
Number Cells (including 12 special half-cells)	96	
Number Bending Magnets	744	
Number Standard Cell Quadrupoles	180	
Number Half-Length Cell Quadrupoles	12	
Number Outer Collins Quadrupoles	12	
Number Inner Collins Quadrupoles	12	
Length of Long Straight Drift Space	54.1347	Meters
Length of Medium Straight Drift Space	28.7682	Meters
Length of Short Straight Drift Space	2.4464	Meters
Length of Short Straight Drift Space in Ends of Half-Cell Replacements	3.048	Meters
Length between Collins Quadrupoles	1.8183	Meters
Length between Magnets and/or Quadrupoles	0.3048	Meters
Length of Bending Magnets	6.2747	Meters
Length of Cell Quadrupoles	1.6899	Meters
Length of Half-Length Quadrupoles	0.84495	Meters
Length of Outer Collins Quadrupoles	3.0	Meters
Length of Inner Collins Quadrupoles	3.4686	Meters
Cell Length	60.9083	Meters
Super-Period Length	1047.20	Meters
Betatron Oscillation Frequency - Radial	20.247	Meters
Betatron Oscillation Frequency - Vertical	20.286	Meters
Betatron Amplitude Function - QF β_H	101.3	Meters
Betatron Amplitude Function - QD	27.7	Meters
Betatron Amplitude Bending Magnets 1, 2, 7, 8	98.5	Meters
Betatron Amplitude Bending Magnets 3, 4, 5, 6	56.2	Meters
Betatron Maximum in Outer Collins Quadrupoles	103.7	Meters
Betatron Maximum in Inner Collins Quadrupoles	80.0	Meters
Closed Orbit Displacement Per $\Delta p/p$ - Maximum	6.843	Meters
Phase Advance Per Cell	70.8	Deg
Phase Advance Per Long Straight 'Half-Cell'	118.0	Deg
Gradient Cell Quadrupole	306.7	Kg/m
Gradient Collins Quadrupole	288.0	Kg/m